Axion Search – CAST

Markus Kuster for the CAST-Collaboration

TU Darmstadt

Astroteilchenphysik in Deutschland: Status und Perspektiven 2005,
DESY, Zeuthen, 2005 October 4

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The Strong CP Problem

QCD predicts that CP (and T) symmetry is broken in strong interactions

This is never observed in experiments !

Symmetry Conservation

	C	P	CP
Electromagn.	Yes	Yes	Yes
Strong	Yes	Yes	Yes
Weak	No	No	No

Example: Violation of CP symmetry $\Longrightarrow$ electric dipole moment of the neutron

Prediction:

$$\boxed{|d_\mathrm{n}| < \bar{\Theta} \cdot 10^{-16}\, e\,\mathrm{cm}}$$

Present experimental limit: $|d_\mathrm{n}| < 10^{-25}\, e\,\mathrm{cm}$

Difference of a factor of $\bar{\Theta} = 10^{-9}$ between theory and experiment !

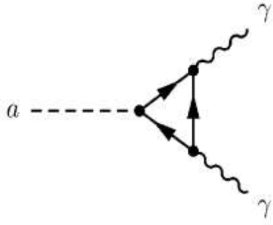
A possible solution:

Exclude all CP violating terms in QCD Lagrangian density by introducing a new component.

The Axion

The Peccei & Quinn Solution (1977)

A new massless pseudoscalar field $a(x)$ interacting with the gluon field, later interpreted as particle by Weinberg, Wilczek 1978.



- Pseudoscalar particle similar to π^0

  $\Longrightarrow$ axions are CP odd by construction

$$a \xrightarrow{CP} -a$$

- Light neutral Goldstone boson that couples to two photons

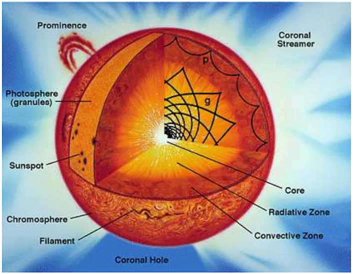
- Astrophysical and cosmological arguments limit axion mass to:

$$10^{-6} < m_\mathrm{a} < 1.2\,\mathrm{eV}/\mathrm{c}^2$$

- Very weak interaction probability with matter $\Longrightarrow$ e.g. lifetime $\tau_{\mathrm{a}\to 2\gamma}$ $\tau_{\mathrm{a}\to 2\gamma} \approx 10^{24}(1\,\mathrm{eV}/m_\mathrm{a}) \Longrightarrow$ for $m_\mathrm{a} \lesssim 25\,\mathrm{eV}/\mathrm{c}^2$ $\tau \geq t_{\mathrm{Universe}}$
- Viable dark matter candidate for $10^{-6}\,\mathrm{eV}/\mathrm{c}^2 < m_\mathrm{a} < 1.2\,\mathrm{eV}/\mathrm{c}^2$

Solar Axions

The Sun

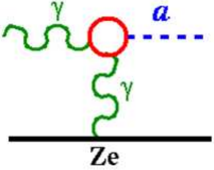


Basic Properties:

Luminosity $L_\odot$	3.8×10^{26} W
Core Temperature	1.5×10^{7} K
Core Density	1.5×10^{2} g cm^{-3}
Mass $M_\odot$	2×10^{30} kg
Radius $R_\odot$	7×10^{8} m
Age	4×10^{9} yr

Primakoff Effect

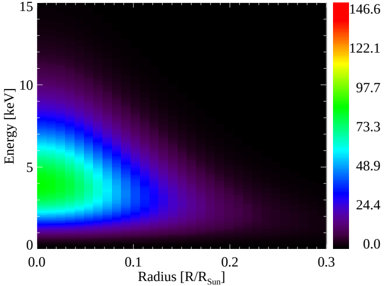
Conversion of thermal photons which couple to the Coulomb field of the plasma in the core of the sun.

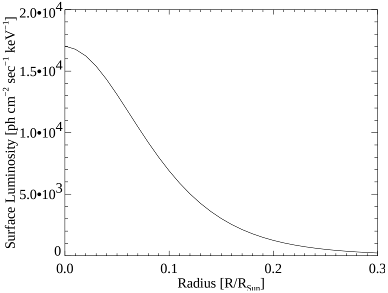


- Process is most efficient for $R < 0.2\,R_\odot$
- Expected mean axion energy $E_a \approx 4.2\,\text{keV}$

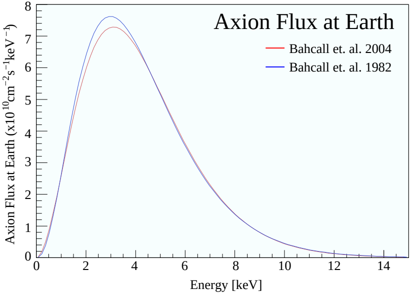
Solar Axion Model

Axion Surface Luminosity





Differential Axion Spectrum



Mean energy: $< E >= 4.2\,\mathrm{keV}$

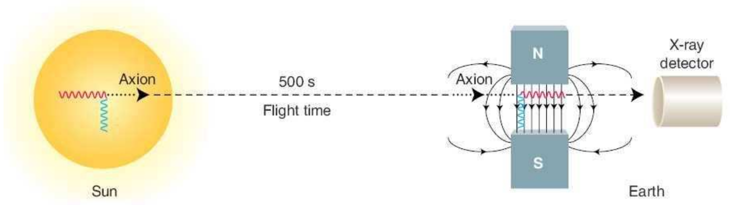
Axion Luminosity:

$$L_\mathrm{a} = 1.9 \times 10^{-3} L_\odot$$

Axion flux: $\Phi_\mathrm{a} = 3.8 \times 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Provided by Serpico & Raffelt
Based on the standard solar model BP2004 (Bahcall et al., 2004)

CAST Principle



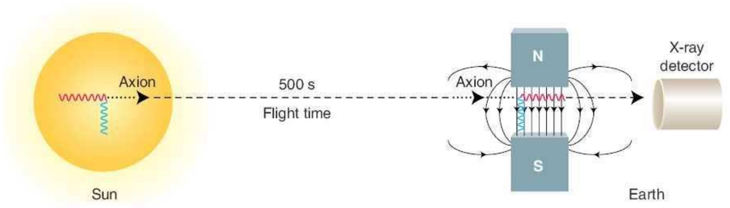
Principle of the Axion Helioscope **Sikivie, Phys. Rev. Lett. 51 (1983)**

- Assumption: Axions are produced via Primakoff effect in the sun
- Point a strong magnetic field towards the sun to convert axions back to X-ray photons
- Use background optimized X-ray detectors to observe the X-rays

Advantages

1. Essentially assumption-free and model-independent
2. Covers a broad-band mass range $m_\mathrm{a} \approx 10^{-16}$–$0.8\,\mathrm{eV}/\mathrm{c}^2$

CAST Principle



Efficiency of the Axion to Photon Conversion (CAST Phase I 2002–2004)

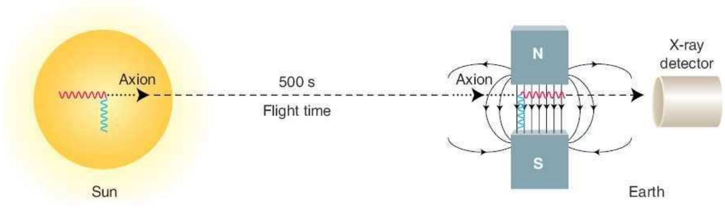
In Vacuum:

$$\boxed{P_{a\rightarrow\gamma} = 1.74 \times 10^{-17} \left(\frac{B\cdot L}{9.0\,\mathrm{T}\cdot 9.26\,\mathrm{m}}\right)^2 \left(\frac{g_{\mathrm{a}\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2 \cdot |M|^2}$$

$$|\vec{q}| = \left|\frac{m_{\mathrm{a}}^2}{2E_{\mathrm{a}}}\right| \qquad |M|^2 = \frac{2(1-\cos(qL))}{(qL)^2} \qquad qL \ll 1 \Longrightarrow |M|^2 = 1$$

For axion masses $m_{\mathrm{a}} > 10^{-2}\,\mathrm{eV}/\mathrm{c}^2$ coherence is lost !

CAST Principle



Expected Solar Axion Flux/Photon Flux

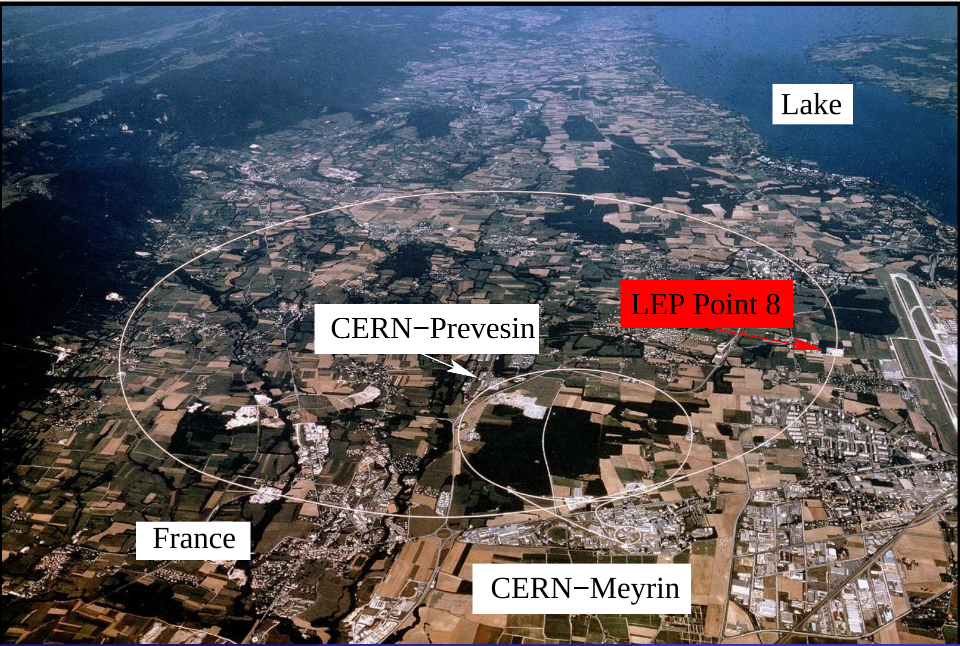
Expected solar axion flux from the Sun:

$$\boxed{\Phi_{\mathrm{a}} = g_{10}^2\, 3.77 \times 10^{11}\,\mathrm{axions\,cm^{-2}\,sec^{-1}}\ \text{with}\ g_{10} = g_{\mathrm{a}\gamma} \times 10^{10}\,\mathrm{GeV}}$$

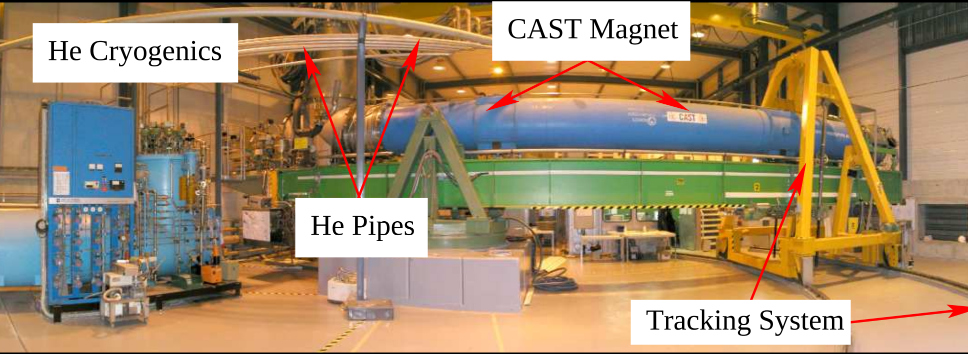
Expected corresponding photon flux:

$$\boxed{\Phi_\gamma = 0.51\, g_{10}^4 \left(\frac{L}{9.26\,\mathrm{m}}\right)^2 \left(\frac{B}{9\,\mathrm{T}}\right)^2 \mathrm{photons\,cm^{-2}\,d^{-1}}}$$

CAST at CERN



CAST at SR8



Prototype LHC magnet

$$B = 9.0\,\mathrm{T} \quad l = 9.26\,\mathrm{m}$$
$$T = 1.8\,\mathrm{K} \quad m \approx 30\,\mathrm{t}$$

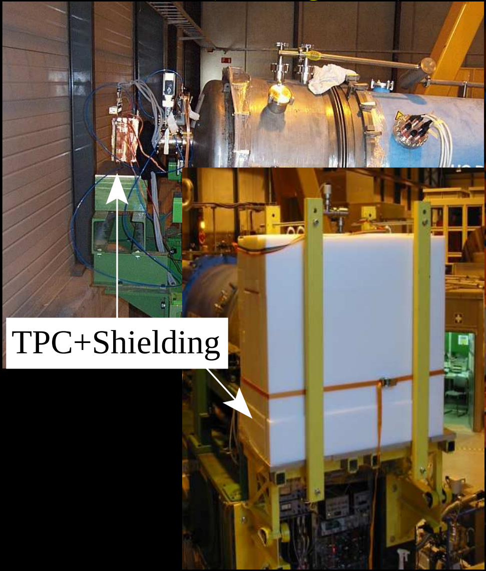
Tracking system

$H = -8^\circ \ldots 8^\circ$ $Az = 40^\circ \ldots 140^\circ$

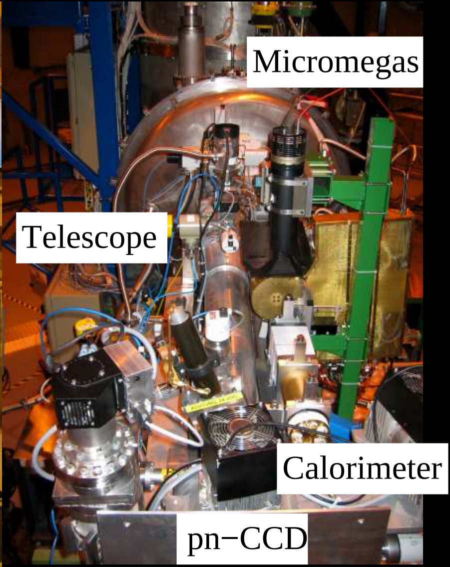
$\Longrightarrow$ 1.5 h observation time during sun rise and sun set ($\approx$ 46 days/year)

The X-ray Detectors

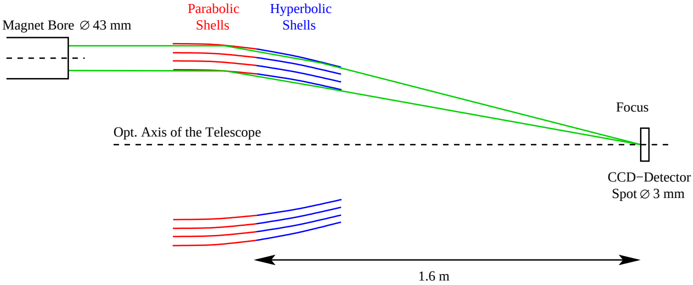
East–side (setting Sun)

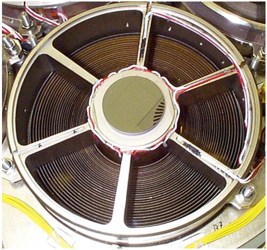


West–side (rising Sun)



The X-ray Telescope of CAST



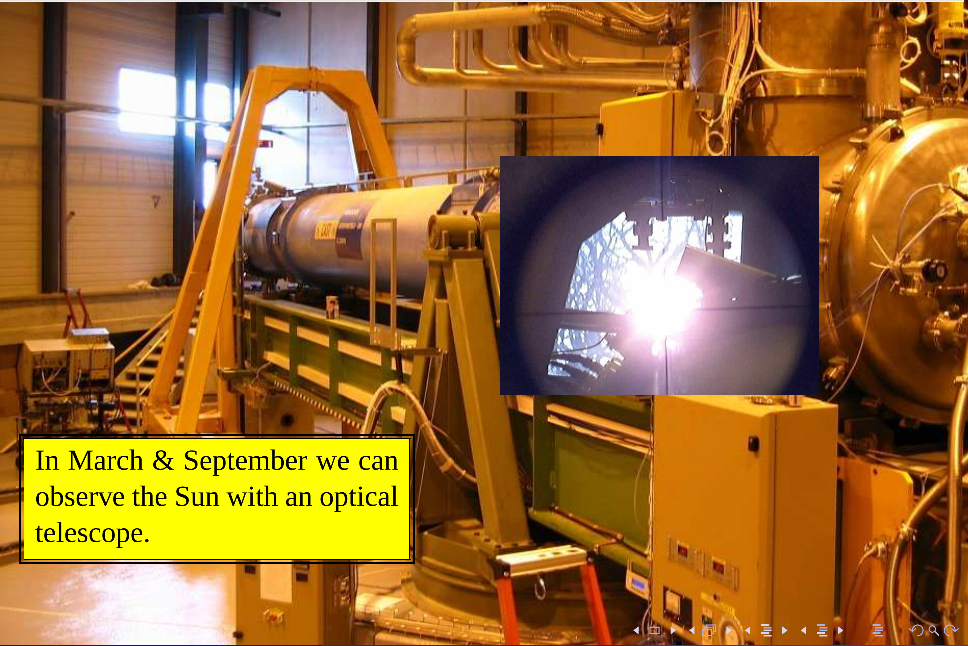


Wolter I type grazing incident optics (prototype for ABRIXAS mission):

- 27 nested gold coated nickel shells, on-axis resolution $\approx$ 43 arcsec
- Telescope aperture 16 cm, used for CAST 43 mm
- Only one sector of the full aperture is used for CAST

$\varnothing$43 mm (LHC Magnet aperture) $\Longrightarrow$ $\varnothing$3 mm (spot of the sun)
Significantly improves the signal to background ratio !

Sun Filming

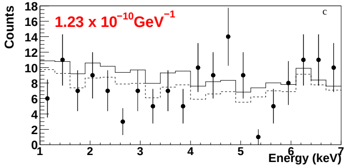


In March & September we can observe the Sun with an optical telescope.

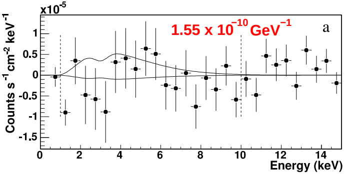
Status of the Experiment

- Two data taking periods in 2003 and 2004 successfully finished (sensitive to axion masses $m_\mathrm{a} < 0.02\,\mathrm{eV}/\mathrm{c}^2$).
  No significant signal over background
  $\Longrightarrow$ improved upper limit on $g_{\mathrm{a}\gamma}$ by a factor of 5
- Total amount of acquired data in 2003:
  Axion sensitive conditions 121.3 h
  Background data 1233.5 h
- Total amount of acquired data in 2004:
  Axion sensitive conditions 179.4 h
  Background data 1723.5 h
- At present CAST is transformed into a new configuration that allows to extend the sensitivity of the experiment to higher axion masses ($0.02\,\mathrm{eV}/\mathrm{c}^2 \leq m_\mathrm{a} \leq 0.8\,\mathrm{eV}/\mathrm{c}^2$).
- Data taking with extended sensitivity is planned for the end of 2005 and 2006/2007.

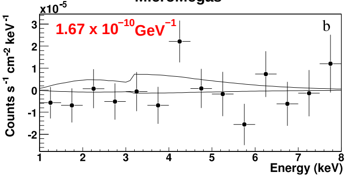
CAST First Results – Data of 2003



pn−CCD

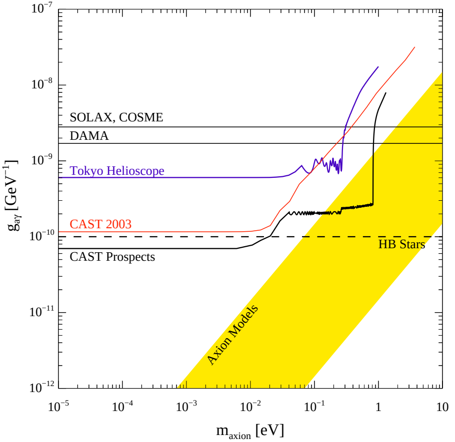


TPC



MicroMegas

Axion Exclusion Plot

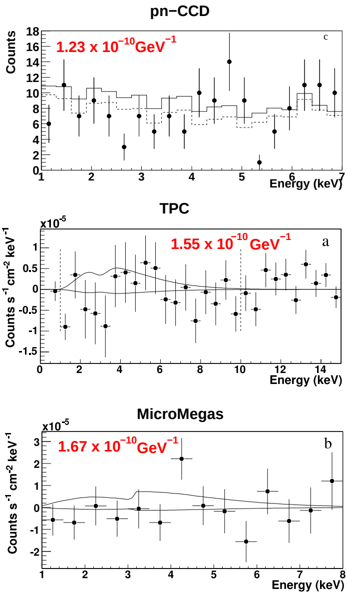


Combined upper limit:

$$\boxed{g_{a\gamma}(95\%) = 1.16 \times 10^{-10}\ \mathrm{GeV}^{-1}}$$

Zioutas et al., Phys. Rev. Lett. 94 (2005) 121301

CAST First Results – Data of 2003



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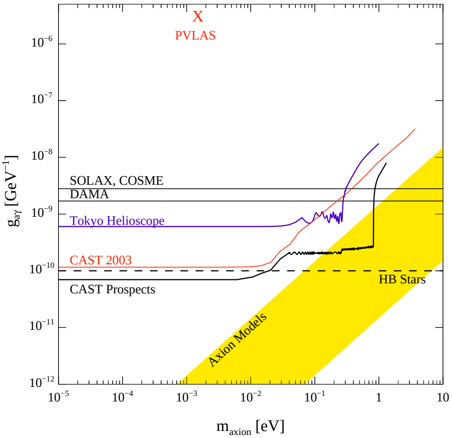

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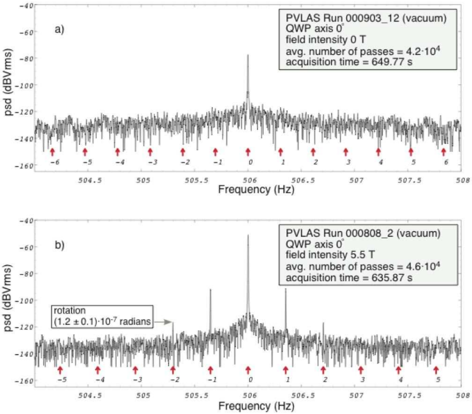
PVLAS - Observed Optical Rotation in Vacuum



Zavattini et al., hep-ex/0507107

- Use a polarized laser beam in vacuum
- Add a transverse magnetic field $B \approx 5.5\,\mathrm{T}$
- Measure change in the state of polarization of the laser
- Change of polarization angle and ellipticity observed.
- Signal was observed at 2 different wavelengths.

Interpretation as neutral, light boson $0.7\,\mathrm{meV} \lesssim m_\mathrm{b} \lesssim 2\,\mathrm{meV}$
$1.6 \times 10^{-6}\,\mathrm{GeV}^{-1} \lesssim g_{\mathrm{b}\gamma} \lesssim 1 \times 10^{-5}\,\mathrm{GeV}^{-1}$

BNL E840 - Optical Rotation Data

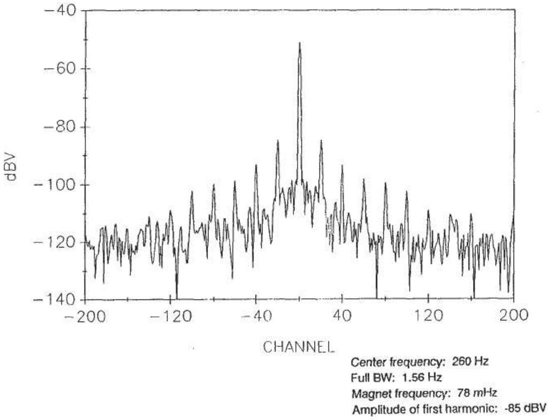


Figure 5.4: Vacuum ellipticity data

Y. Semertzidis (priv. comm.)
and Y. Semertzidis, 1990, PhD Thesis, Uni. Rochester

- Experiment based on the same physical principle, but different experimental setup.
- Similar signal was observed in the E840 experiment.

CAST Phase II

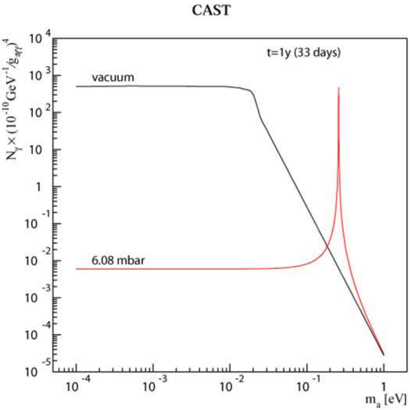
Fill magnet bore with buffer gas

^{4}He or ^{3}He

($p_{\text{vap}} = 16/140\,\text{mbar}@1.8\,\text{K}$)

$\Longrightarrow$ photon acquires an effective mass

$$\boxed{m_{\gamma,\text{eff}} \approx \sqrt{0.02\frac{P[\text{mbar}]}{T[\text{K}]}}\,[\text{eV}/\text{c}^2]}$$



Systematically change pressure $\Longrightarrow$ scan mass range $m_a > 0.02\,\text{eV}/\text{c}^2$

- ^{4}He: ≈ 74 pressure steps $0 \leq p \leq 6\,\text{mbar}$, $m_a \leq 0.26\,\text{eV}/\text{c}^2$
- ^{3}He: ≈ 590 pressure steps $6 < p \leq 60\,\text{mbar}$, $m_a \leq 0.8\,\text{eV}/\text{c}^2$

$\Longrightarrow$ Allows to scan axion masses $0.02\,\text{eV}/\text{c}^2 \leq m_a \leq 0.8\,\text{eV}/\text{c}^2$

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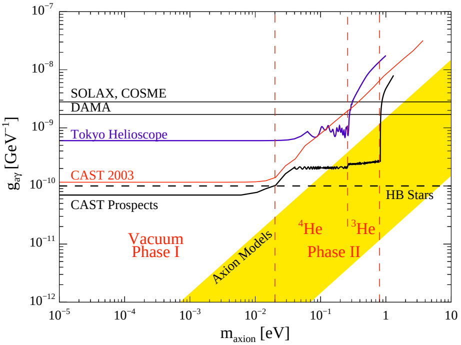

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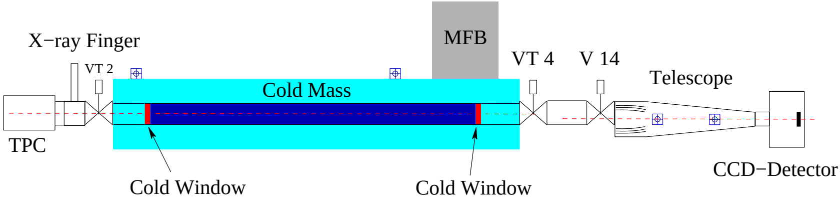
CAST – Transforming to Phase II



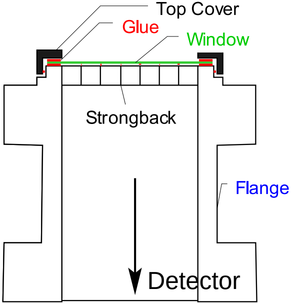
Cold Windows/He-Gas System

- System to control the density and temperature of the gas in the bore
- Gas system to store the ^{4}He/^{3}He gas
- Cold windows to separate gas volume to vacuum of the detectors minimizing thermal coupling between the cold bore → outside of the magnet

Approach: Start with a simplified ^{4}He system → go to ^{3}He system

Cold Windows R&D – Saclay – CERN – Freiburg

Prototype Cold Window 2005



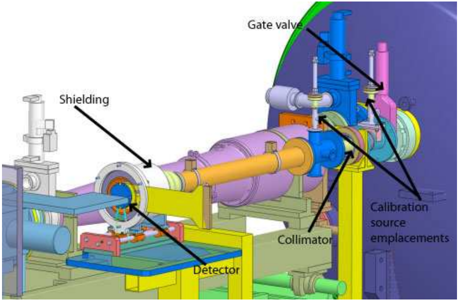
Technical Requirements

- High transmissivity at 1–7 keV
- Minimizing He leak rate $q_{^4\mathrm{He}} < 10^{-8}\,\mathrm{mbar\,l/s}$ at 1.8 K
- Transparent in the optical $\Longrightarrow$ alignment of the telescope
- Withstand pressure differences during a "Quench" ($\approx$ 1 bar)
- Robust under normal operating conditions

Technical requirements constrain the design of the window and the selection of the material.

LLNL Telescope and Saclay Micromegas

Micromegas with X-ray Optics



Detector Concept

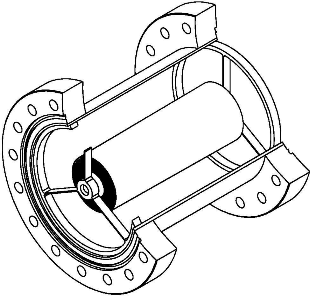
- Integrated shielding based on TPC experience
- Better conversion probability (88% compared to 73% 2004)
- Integrated calibration and alignment sources

X-ray Optics

- Concentrator with a focal length of 1.3 m and diameter ≈ 47 mm
- 14 nested 125 mm long Iridium coated Polycarbonate shells
- 2 mm spot diameter and throughput ≈ 36%

LLNL Telescope and Saclay Micromegas

Concentrator



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CAST 2005 and Beyond

Schedule 2005–2007

2005 2. Half	Test of the ^{4}He system (running)
	Open cryostat, install cold windows for 2005
	Commissioning
	Short data taking run
2006 1. Half	Final cryostat modifications, install ^{3}He system
	Installation of the final cold windows
	Installation of the new MM telescope/detector + alignment
	Grid measurements
2006 2. Half	Test data taking run + commissioning
	Full data taking
2007 1. Half	Short shutdown for maintenance
	Full data taking
2007 2. Half	Full data taking

Conclusions

- The CAST collaboration has published its first results and derived a new upper limit on $g_{\mathrm{a}\gamma}$.
- No significant signal over background could be observed in 2003 and 2004 (analysis is in progress)
- All detectors showed optimal performance during the 2004 data taking run $\Longrightarrow$ 6 months of data.
- CAST 2004 data allows to exploit the full potential of the telescope.
- The CAST magnet is in preparation for the 2005 ^{4}He runs.
- LLNL joined the collaboration and will provide the ^{3}He for Phase II of CAST.
- An additional LLNL telescope system and Micromegas detector is under development for Phase II (2006).
- A promising signal was reported by the PVLAS collaboration $\Longrightarrow$ needs to be confirmed.

And ...

Joint ILIAS–CAST–CERN Axion Training 2005

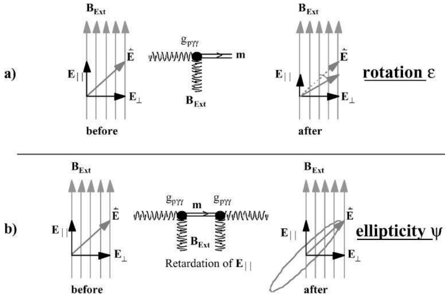
30. November – 02. December 2005
CERN, Geneva
+
Workshop on Low Energy Axions

Speakers: Karl van Bibber, Eduard Masso, Roberto Peccei, Georg Raffelt, Yannis Semertzidis, Pierre Sikivie ...

Registration + Program:
http://cast.mppmu.mpg.de/axion-training-2005/axion-training.php

Deadline: 21. October 2005

PVLAS – Dichroism/Ellipticity



1. Real production of a particle
   Component parallel to $\vec{B}$ will be reduced $\Longrightarrow$ rotation of the polarization plane
2. Production and decay of a virtual particle
   Retardation between $E_{\|}$ and $E_{\perp}$ $\Longrightarrow$ change in ellipticity Ψ

Experimental Principle

- Use a polarized laser beam in vacuum
- Add a transverse magnetic field
  $$B \approx 5.5\,\mathrm{T}$$
- Measure change in polarization state of the laser beam

Results

Measured ellipticity:

$$\Psi \approx 10^{-7}$$

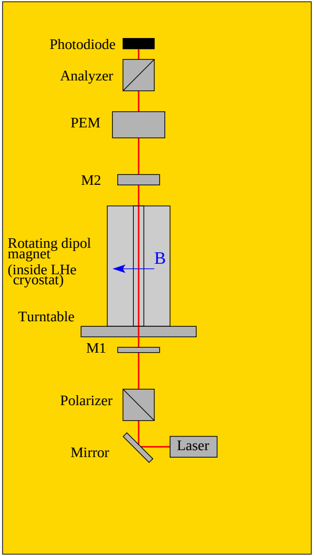
QED predicted ellipticity:

$$\Psi \approx 10^{-11}$$

U. Gastaldi, la Thuile, 2004

PVLAS – Experimental Setup

PVLAS Resonant Optical Cavity

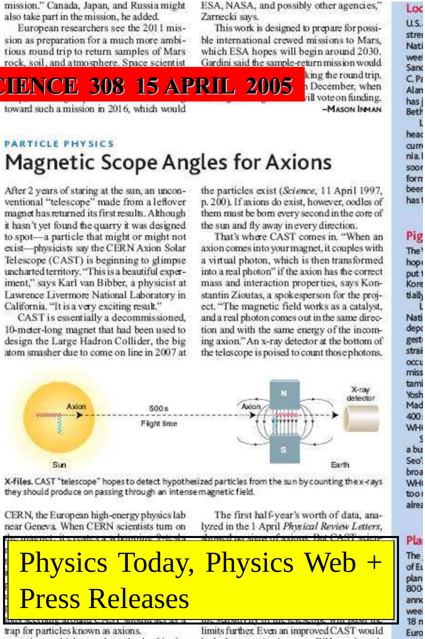


- 1 m long, superconducting dipole magnet
  rotating with $f = 0.33\,\mathrm{Hz}$
  Magnetic field $B = 5.5\,\mathrm{T}$
- Fabry-Perot resonator with two mirrors M1, M2
  (optical path $\approx 60\,\mathrm{km}$)
- Nd:YAG IR laser $\lambda = 1064\,\mathrm{nm}$
- PEM: Photo Elastic Modulator to measure very small ellipticities

For details see:
F. Brandi et al., NIM A, 2001, 461

CAST First Results – Data of 2003

SCIENCE 308 15 APRIL 2005



mission." Canada, Japan, and Russia might also take part in the mission, he added.

European researchers see the 2011 mission as preparation for a much more ambitious round trip to return samples of Mars rock, soil, and atmosphere. Space scientist

toward such a mission in 2016, which would

ESA, NASA, and possibly other agencies," Zarnecki says.

This work is designed to prepare for possible international crewed missions to Mars, which ESA hopes will begin around 2030. Gardini said the sample-return mission would

king the round trip.

n December, when

vill vote on funding.

–Mason Inman

PARTICLE PHYSICS

Magnetic Scope Angles for Axions

After 2 years of staring at the sun, an unconventional "telescope" made from a leftover magnet has returned its first results. Although it hasn't yet found the quarry it was designed to spot—a particle that might or might not exist—physicists say the CERN Axion Solar Telescope (CAST) is beginning to glimpse uncharted territory. "This is a beautiful experiment," says Karl van Bibber, a physicist at Lawrence Livermore National Laboratory in California. "It is a very exciting result."

CAST is essentially a decommissioned, 10-meter-long magnet that had been used to design the Large Hadron Collider, the big atom smasher due to come on line in 2007 at CERN, the European high-energy physics lab near Geneva. When CERN scientists turn on

trap for particles known as axions.

the particles exist (*Science*, 11 April 1997, p. 200). If axions do exist, however, oodles of them must be born every second in the core of the sun and fly away in every direction.

That's where CAST comes in. "When an axion comes into your magnet, it couples with a virtual photon, which is then transformed into a real photon" if the axion has the correct mass and interaction properties, says Konstantin Zioutas, a spokesperson for the project. "The magnetic field works as a catalyst, and a real photon comes out in the same direction and with the same energy of the incoming axion." An x-ray detector at the bottom of the telescope is poised to count those photons.

The first half-year's worth of data, analyzed in the 1 April *Physical Review Letters*,

limits further. Even an improved CAST would

X-files. CAST "telescope" hopes to detect hypothesized particles from the sun by counting the x-rays they should produce on passing through an intense magnetic field.

Physics Today, Physics Web + Press Releases

research highlights

DNA sequencing

Different dyes for clear-cut colours

Proc. Natl Acad. Sci. USA 102, 5346–5351 (2005)

Since its introduction almost 20 years ago, four-colour DNA sequencing has largely relied on the same, somewhat error-prone, method. Now Ernest K. Lewis *et al.* have built a prototype sequencing machine that could improve accuracy.

In conventional colour sequencing, the chemical bases that make up DNA are tagged with fluorescent dyes — a different colour for each of the four bases. A machine shines a laser onto the DNA molecules, and detects the wavelength of light emitted from each base to determine their sequence. But mistakes happen, partly because the spectra produced by the dyes overlap, and hence the glow from one dye can be mistaken for that from another.

For the new method, called pulsed multiline excitation, the researchers developed a different set of four fluorescent dyes, each of which is excited by a separate wavelength. Their machine fires a series of four laser beams at the dye, but only the appropriate laser triggers a signal. The method could greatly improve the ease with which one base can be distinguished from another. **Helen Pearson**

Cancer

Remote control

Curr. Biol. 15, 561–565 (2005)

BRCA1 is notorious as the first gene to be linked with inherited susceptibility to breast and ovarian cancer. It has been thought of as a classic 'tumour suppressor', but Rajas Chodankar *et al.* suggest that it may have another, more subtle, effect.

Granulosa cells in the ovary produce the sex hormones that regulate the ovulatory cycle — and the growth of ovarian tumours. Given that repeated ovulations (that is, fewer pregnancies or reduced oral contraceptive use) are known to increase the risk of non-hereditary ovarian cancer, the researchers wondered whether decreased levels of BRCA1 protein in granulosa cells are involved. Using mice, they inactivated the gene specifically in these cells. The animals developed tumours in the ovaries and uterine horns. But the tumour cells looked like epithelial cells and had normal copies of the gene, implying that they had not developed from granulosa cells.

Inactivating *BRCA1* seems, therefore, to be controlling some intermediary produced by the granulosa cells. It is this unidentified

CAST COLLABORATION

Particle physics

The elusive axion

Phys. Rev. Lett. 94, 121301 (2005)

An effect known as charge–parity violation is linked to the fact that the Universe contains far more matter than antimatter, and it is well documented in processes involving the so-called weak nuclear force, one of the four fundamental forces of nature. But it seems to be suppressed by the strong force, and this can be explained by postulating a hitherto undiscovered particle, the axion. Axions interact hardly at all with radiation or other matter, making them hot candidates to be the 'cold dark matter' that is thought to pervade the Universe.

The CAST (CERN Axion Solar Telescope) collaboration has adopted an innovative approach to the search for axions. They are pointing a powerful test magnet (pictured), decommissioned from CERN's Large Hadron Collider, at the Sun. Axions might be produced in the solar plasma when photons are scattered in strong electromagnetic fields. CAST has put the scattering effect into reverse by producing X-ray photons from solar–axion interactions on Earth.

The magnet can be tilted at either end to an angle that allows the Sun to be observed at sunrise and sunset, both ends being fitted with X-ray detectors and an X-ray telescope recycled from the German space programme. The results, assuming a very small axion mass, show no signal above background, and constrain the axion–photon coupling strength by a factor of five compared with results from previous lab experiments. Future measurements should deliver still better sensitivity, and also test the axion hypothesis for higher masses. **Richard Webb**

Neurobiology

Illuminating behaviour

Cell 121, 141–152 (2005)

Through genetic engineering, researchers have developed a new technique for exciting neurons and influencing fruitfly behaviour. Whereas scientists typically excite these cells with electricity, the effect here was achieved with laser light.

Susana Q. Lima and Gero Miesenböck designed fruitflies to express particular ion channels in neurons that control escape mechanisms — such as jumping and wing beating — or in the dopamine-producing cells that influence movement. The next step involved injecting the flies with ATP (energy-storing molecules) held in chemical cages.

A 200-millisecond pulse of laser light — directed at the flies — removed the cage from the ATP molecules, allowing them to stimulate the channels and depolarize the neurons. When the authors targeted the neurons linked to escape mechanisms, the light set off jumping and wing flapping in the fruitflies. Similarly, targeting dopamine-producing cells altered the insects' walking behaviour. The authors speculate that this ability to direct animal behaviour by remote control

Spintronics

How electrons relax

Phys. Rev. Lett. 94, 116601 (2005)

In the burgeoning field of spintronics, binary bits of data are stored in the spins of electrons, rather than in their charge, with a '1' equating to spin up and a '0' to spin down. But one problem facing the development of spintronic devices is that, although electron spin can be manipulated, it tends not to stay so — an induced spin decays as the electron interacts with the magnetic field of nearby nuclei.

P.-F. Braun and colleagues have now directly observed this 'spin relaxation' in quantum dots — clusters of atoms just nanometres across — made of the semiconductor materials indium arsenide and gallium arsenide. The authors found that the initial spin polarization of such dots decays with a half-life of just 0.5 nanoseconds — half a millionth of a millisecond — before remaining stable at about a third of its initial value for at least a further 10 nanoseconds.

However, they also report that this relaxation process can be suppressed by an externally applied static magnetic field of just 100 mT, which can be provided by small permanent magnets. Such a field increases the characteristic decay half-life

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